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Aerts, J.C.J.H.; Renssen, H.; Ward, P.J.; de Moel, H.; Odada, E.; Bouwer, L.M.; Goosen, H.

published in
Geophysical Research Letters
2006

DOI (link to publisher)
10.1029/2006GL027493

document version
Publisher's PDF, also known as Version of record

Link to publication in VU Research Portal

citation for published version (APA)
Aerts, J. C. J. H., Renssen, H., Ward, P. J., de Moel, H., Odada, E., Bouwer, L. M., & Goosen, H. (2006). Sensitivity of global river discharges under Holocene and future climate conditions. *Geophysical Research Letters*, *33 (19)*, 1-5. https://doi.org/10.1029/2006GL027493

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Sensitivity of global river discharges under Holocene and future climate conditions

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Received 18 July 2006; revised 24 August 2006; accepted 30 August 2006; published 3 October 2006.

[1] A comparative analysis of global river basins shows that some river discharges are more sensitive to future climate change for the coming century than to natural climate variability over the last 9000 years. In these basins (Ganges, Mekong, Volta, Congo, Amazon, Murray-Darling, Rhine, Oder, Yukon) future discharges increase by 6–61%. These changes are of similar magnitude to changes over the last 9000 years. Some rivers (Nile, Syr Darya) experienced strong reductions in discharge over the last 9000 years (17–56%), but show much smaller responses to future warming. The simulation results for the last 9000 years are validated with independent proxy data. **Citation:** Aerts, J. C. J. H., H. Renssen, P. J. Ward, H. de Moel, E. Odada, L. M. Bouwer, and H. Goosse (2006), Sensitivity of global river discharges under Holocene and future climate conditions, *Geophys. Res. Lett.*, *33*, L19401, doi:10.1029/2006GL027493.

1. Introduction

[2] Future climate change is expected to have a profound impact on the discharge of the world's major rivers [*Intergovernmental Panel on Climate Change*, 2001; *Milly et al.*, 2005; *Gedney et al.*, 2006; *Falloon and Betts*, 2006]. As a consequence, future human activities and ecosystems that depend on water availability (e.g., agriculture and wetlands) may be severely affected [*Aerts and Droogers*, 2004]. A variety of studies have used both Global Circulation Models and hydrological models to simulate changes in river discharges under changed climatic conditions [*Arora and Boer*, 2001; *Döll et al.*, 2003; *Milly et al.*, 2005]. However, these studies lack an assessment of the sensitivity of river discharge to long-term climate change (>300 years) as discharge measurements cover a rather limited time-span [*Vörösmarty et al.*, 1998; *Alcamo et al.*, 2000; *Meybeck*, 2003; *Ward*, 2005]. To evaluate the effects of future global warming on mean discharge, relative to the effects of natural climatic variability, we simulated the discharge of a number of major river basins for the period 9000 BP until 2100 AD.

[3] For the pre-industrial era (9000 BP-1750 AD), orbitally induced variations in insolation are the dominant forcing mechanism of long-term climate variability [*Opsteegh et al.*, 1998; *Renssen et al.*, 2005]. These insolation variations differ per latitude and per season. In the Northern Hemisphere (NH), the seasonal insolation contrast was larger at 9000 years BP than today, with more insolation being received in summer (between 25 and 45 W m^{-2} more than today) and less in winter (10 to 25 W m^{-2} less than today). At 9000 years BP the seasonal insolation contrast was smaller in the Southern Hemisphere (SH) than it was at that time in the NH. In response to the NH summer insolation maximum, the early Holocene (9000–8000 BP) was a relatively warm and wet period at high northern latitudes [*Opsteegh et al.*, 1998]. In NH tropical regions influenced by summer monsoons, precipitation was greatly enhanced during the early to middle Holocene (9000–5000 BP) due to the high summer insolation values. This caused the preferential heating of the continents, leading to an enhanced land-ocean temperature gradient and strengthened summer monsoons. This effect was amplified by a positive feedback involving vegetation cover: more precipitation resulted in higher vegetation cover and lower surface albedo [*Kutzbach and Street-Perrot*, 1985; *Renssen et al.*, 2005; *Roberts*, 2002].

2. Methods

[4] Firstly, the atmosphere-ocean-vegetation model ECBilt-CLIO-VECODE was used to perform a transient simulation of the last 9000 years, forced by changes in orbital parameters and greenhouse gas concentrations [*Opsteegh et al.*, 1998; *Brovkin et al.*, 2002; *Goosse et al.*, 2005]. This experiment was subsequently continued until 2100 AD, the greenhouse gas concentrations being forced by anthropogenic scenario SRES A2. This scenario prescribes a gradual increase in CO_2 between 1750 and 2100 AD, culminating with concentrations circa 2.5 times those of 1990 [*Intergovernmental Panel on Climate Change*, 2001], and inducing a general warming trend over the period. The simulation results for the period 1750–2100 AD show a general warming trend as a response to increasing greenhouse gas concentrations, which overwhelms the longer-term effect of orbital forcing on this time-scale. Although other factors also play a role (e.g., solar variability, volcanic eruptions, sulphate aerosols, anthropogenic land-use changes, carbon dioxide enrichment, etc.), we restrict ourselves to the forcings that are dominant on long time-scales. The climate model has a relatively low sensitivity (1.8°C) to a doubling of atmospheric CO_2 concentration compared to other climate models [*Goosse and Fichefet*, 1999].

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Table 1. Percent Precipitation Change Relative To the Current Situation for the Four Time Slices[a]

River	Early Holocene 9000–8600 BP Percent Change	Middle Holocene 6200–5800 BP Percent Change	Recent 1750–2000 AD Mean	Recent 1750–2000 AD 2 SD	Future 2001–2099 AD Percent Change
Volta	16.6	8.4	12719	4.0	16.1
Mekong	−0.6	−4.5	10197	8.2	6.6
Ganges	8.0	−0.2	14596	5.1	10.6
Murray Darling	−1.3	0.1	3856	13.4	12.8
Syr Darya	17.6	16.1	6597	12.2	−2.0
Nile	19.6	11.1	10154	5.2	16.3
Congo	−2.0	−1.9	15289	2.9	4.1
Amazon	−1.5	−0.3	14041	2.6	6.5
Oder	1.2	2.1	4585	9.0	5.8
Rhine	−3.7	−2.2	7787	6.3	8.1
Danube	9.0	7.3	4438	12.7	2.3
Volga	4.5	4.7	4146	4.4	5.7
Mississippi	3.4	7.7	6967	17.7	−6.5
Lena	3.3	1.7	5339	3.7	6.4
Yukon	11.5	7.0	5651	5.8	12.8

[a]Two standard deviations (2 SD) refers to two times the standard deviation (%) of the recent time slice. In the recent time slice, precipitation means are listed as decadal totals.

[5] Secondly, the monthly climate and vegetation cover data simulated by ECBilt-CLIO-VECODE have been used as input to the calibrated hydrological model called STREAM [*Kwadijk*, 1993; *Aerts et al.*, 1999; *Ward*, 2005]. Tables 1 and 2 list simulated average climate data (precipitation and temperature) over four time slices. Downscaling and redistribution techniques were applied in order to prepare the climate model outputs as input for the STREAM model [*de Moel*, 2005]. The STREAM model was set up for different global river basins distributed over a wide range of geographical and climatic zones around the globe. North American river basins are not included in the analyses before 6000 BP, as the influence of the Laurentide Ice Sheet during the early Holocene is not simulated in the coupled model. Note that we compared the simulated Holocene and future discharge trends to the simulated average decadal discharges for the recent time slice (1750–2000 AD). In some instances the simulated future trends deviated from those found in other studies [*Arora and Boer*, 2001; *Nijssen et al.*, 2001; *Manabe et al.*, 2004; *Milly et al.*, 2005]. These differences can probably be attributed to differences in climatic forcings caused by the use of different climate models in the various studies and to differences in the reference period which in most studies is selected as the period 1961–1990. In this study the reference period 1750–2000 is used in order to have enough data for calculating the interdecadal variability (see Table 3). Also in this context note that we did not include other anthropogenic effects on river basins, such as obstruction and water withdrawal.

3. Results

[6] The Holocene discharge trends in tropical monsoon river basins influenced by NH summer monsoons closely follow the orbitally forced decrease in precipitation. Between 9000 years BP and 1750 AD, the mean discharges of the Asian Mekong and Ganges rivers decreased by 28% and

Table 2. Absolute Temperature Change Relative To the Current Situation for the Four Time Slices[a]

River	Early Holocene 9000–8600 BP Change, °C	Middle Holocene 6200–5800 BP Change, °C	Recent 1750–2000 AD Mean	Recent 1750–2000 AD 2 SD	Future 2001–2099 AD Change, °C
Volta	−0.42	−0.35	32.0	0.26	0.81
Mekong	−0.33	−0.15	27.9	0.50	0.85
Ganges	−0.23	−0.44	19.7	0.49	1.58
Murray Darling	−0.18	−0.25	23.3	0.33	0.74
Syr Darya	−0.46	−0.37	11.7	0.80	2.05
Nile	−0.27	−0.21	29.7	0.27	0.96
Congo	−0.05	−0.05	28.2	0.21	0.74
Amazon	−0.17	−0.25	29.4	0.24	0.73
Oder	0.25	0.06	13.8	0.70	1.68
Rhine	0.55	0.27	13.1	0.45	1.36
Danube	0.24	0.05	17.0	0.58	1.36
Volga	−0.22	−0.15	6.7	0.97	2.39
Mississippi	−0.16	−0.35	17.6	0.97	2.17
Lena	−0.19	−0.18	−10.8	0.79	2.42
Yukon	1.40	0.69	−4.2	1.00	2.97

[a]Two standard deviations (2 SD) refers to two times the standard deviation of the recent time slice.

Table 3. Comparison of Modeled Mean Decadal Discharges and Discharges Implied From the Proxy Data for Four Time Slices[a]

	Early Holocene 9000–8600 BP			Middle Holocene 6200–5800 BP			Recent 1750–2000 AD			Future 2001–2099 AD
							Mean Decadal Discharge			
	Mean Decadal Discharge (%)	Proxy, + / = / −	Agreement	Mean Decadal Discharge (%)	Proxy, + / = / −	Agreement	Modeled 1750–2000, $m^3\ s^{-1}$	Observed 20th Century, $m^3\ s^{-1}$	Interdecadal Variability 2 SD, %	Mean Decadal Discharge (%)
Very Sensitive										
Volta	+70[b,c]	+ +	Good	+43[b,c]	+	Good	1247	1212	13	+61
Mekong	+28[b]	+ +	Good	+17[b]	+	Good	728	715	N/A	+37
Ganges	+30[b,c]	+ +	Good	+7[b,c]	= / +	Good	10526	10813	8	+29
Murray-Darling	−24[b]	−	Good	−4[b]	+	Poor	222	257	N/A	+43
Sensitive										
Syr Darya	+56[b,c]	+	Good	+23[b]	+	Good	545	692	N/A	−1
Nile	+17[b,c]	+ +	Good	+9[b]	+	Reasonable	2576	2462	9	−2
Congo	+6[b]	+ +	Reasonable	+5[b]	+	Reasonable	38821	39706	7	+12
Amazon	−3[b]	−	Reasonable	−1[b]	−	Reasonable	152715	155240	3	+6
Low Sensitivity										
Oder	−1[b,c]	=	Good	+2[b,c]	=	Good	528	536	16	+15
Rhine	+1[b,c]	=	Good	0[b,c]	=	Good	2271	2291	8	+8
Danube	+12[b,c]	=	Good	+9[b,c]	=	Good	6540	6499	19	−2
Volga	+6[b]	+	Reasonable	+7[b,c]	=	Good	7940	8205	10	+4
Mississippi	NS	−	Poor	+9	+	Reasonable	15479	14795	30	−19
Lena	−3[b,c]	=	Good	−2[b,c]	=	Good	16772	16622	8	0
Yukon	NS	+	Poor	0	=	Good	6036	6109	12	+5

[a]Proxy data are in *Ward* [2005]. Simulated discharges are given as percentage changes relative to discharges in the recent time slice. The paleo-discharges as inferred from the proxy data are indicated as relative changes in direction compared to the *recent* time-slice (++/+/ = /−/−−). The variation in recent discharges is expressed in the column ‘interdecadal variability’ as two times the standard deviation 2 SD (%) of the recent time slice. N/A means the variability has not been calculated since the mean discharges are not normally distributed. NS indicates that this period has not been simulated due to the presence of the Laurentide Ice Sheet.

[b]The model and proxy data are in agreement according to the mean test.

[c]The model and proxy data are in agreement according to the variability test.

30%, respectively (Figure 1 and Table 3). Similarly, simulations for the African basins Congo, Nile and Volta show a reduction in average decadal discharges by 6%, 17% and 70% respectively. The relatively small decrease in the discharge of the Congo can be explained by its lower latitude location (between 15°S and 7°N), and by a later rainy season compared to the other basins (September–November, vs. June–July). For this latitude and season, the orbitally forced insolation maximum is smaller than that of the other basins discussed.

[7] The discharges of the Ganges, Mekong, Volta and Congo rivers respond strongly to the future greenhouse gas

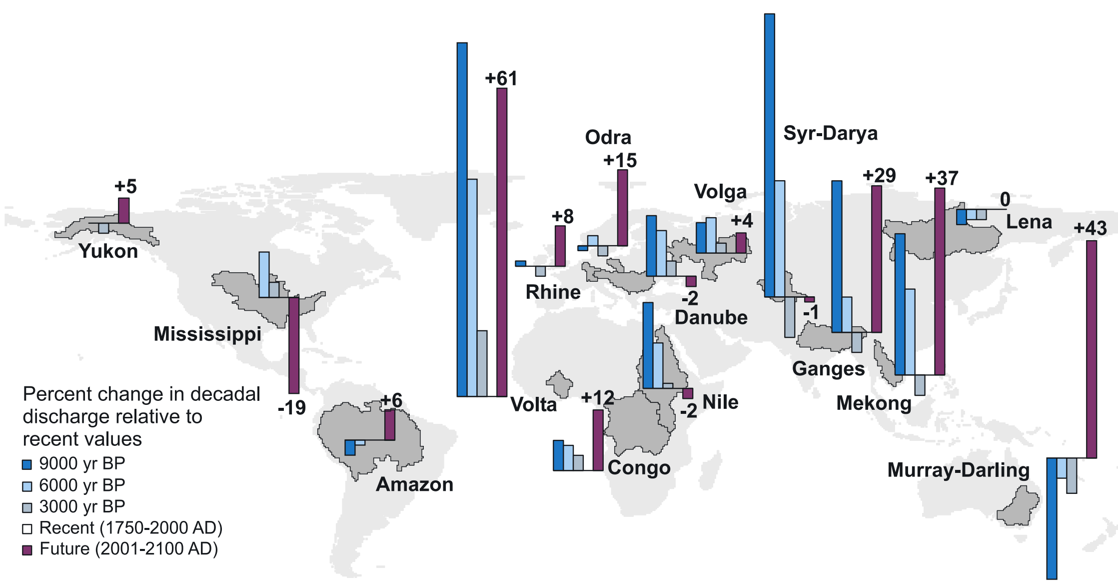

Figure 1. Percentage change in decadal discharges for fifteen global river basins. The bars represent averages over 9000-8600 BP, 6200-5800 BP, 3000-2600 BP and 2001–2099 AD, as compared to the average recent time period of 1750–2000 AD.

forcing scenario with increases in mean decadal discharge of between 12–61% compared to the recent discharge values (Figure 1 and Table 3). This implies that river discharges in these basins will have a similar or greater response to the projected anthropogenic climate change of the next 100 years, than they had to the natural climatic variations of the last 9000 years. These figures for the 21st century are in line with those from previous climate impact research [*Manabe et al.*, 2004; *Milly et al.*, 2005]. For the Congo such studies have simulated either increasing or similar discharges in the future [*Manabe et al.*, 2004; *Milly et al.*, 2005]. Compared to the current situation (average over 1750–2000 AD) future Nile discharge will remain relatively stable, or decrease slightly (−2%). This can be attributed to reduced soil moisture conditions in the future, due to a rapid increase in average temperatures: the latter are projected to be much higher than at 9000 years BP.

[8] In contrast to the rivers in monsoonal regions, the simulated discharge of the Amazon was lower at 9000 years BP than today (−3%). This is related to reduced insolation during the main rainy season between December and April, resulting in lower surface temperatures and reduced convective precipitation. The Amazon shows a slow increase in mean discharge during the Holocene, starting at 3% lower than today in the early Holocene. This is not confirmed by other studies where a profound decrease in precipitation and runoff is projected [*Arnell*, 2003; *Betts et al.*, 2004; *Falloon and Betts*, 2006]. A similar result is found for another SH basin, the Murray-Darling, which shows an increase in mean discharge during the Holocene starting with 20% lower discharges than today at 9000 years BP.

[9] Both of the SH basins studied show an upward trend in river discharge under the future climate warming scenario, with simulated discharge increases of 6% and 43% for the Amazon and Murray-Darling respectively [*Schreider et al.*, 1996]. Consequently, the magnitude of change in simulated mean discharge for the coming 100 years is greater than that simulated for the last 9000 years. The sign of the change is however reversed, because in the early Holocene the rainy season was cooler than today, as opposed to a warmer rainy season in the future.

[10] At mid-latitudes, precipitation is more evenly distributed over the year compared to low-latitudes. This infers that the impact of the positive NH summer insolation anomaly in the early Holocene should be smaller, as it is partly compensated by the negative winter insolation anomaly. This inference is especially valid for basins in a maritime setting such as the Rhine and Oder, for which the simulated Holocene discharges show little deviation compared to current average decadal discharges. The Volga and Danube river basins have a more continental setting and receive most precipitation in summer. As a result, they show a 6% (Volga) and 12% (Danube) decrease in simulated discharges during the Holocene. The Mississippi basin also shows a decrease in discharge (−9%) from 6 ka BP, mainly due to a decrease in precipitation. The Syr Darya basin shows a sharp decline in discharge, which can be explained by decreasing precipitation and slightly increasing temperatures during the Holocene.

[11] Both the Rhine (+8%) and Oder (+15%) rivers react strongly to the future climate-warming scenario, due to a net increase in precipitation in these basins [*Middelkoop et al.*, 2001; *Manabe et al.*, 2004]. Furthermore, climate change projections show that the discharges of the Danube and Syr Darya remain similar (−2% and −1% respectively), and that the discharge of the Mississippi decreases strongly (−19%). Although future temperatures in these basins increase, the projected precipitation decrease of the Danube (−2%) is less than that of the Mississippi due to continuing convective precipitation in the western parts of the Danube basin. Furthermore, temperatures in the Volga basin increase as well as precipitation, leading to a slight increase in Volga discharge (4%) [*Arora and Boer*, 2001; *Milly et al.*, 2005].

[12] The arctic Lena and Yukon basins show minor changes in mean discharge during the Holocene as compared to the current situation (−3% Lena; +1% Yukon at 5000 ka BP). Future mean discharges under climate change show no alteration for the Lena and an increase for the Yukon (+5%). Both rivers show a seasonal shift in discharge distribution due to earlier snow melt. Other studies confirm this trend, but project higher increases in Arctic discharges [*Nijssen et al.*, 2001; *Manabe et al.*, 2004].

4. Conclusions

[13] Our study has shown that future climate change as a result of increased atmospheric greenhouse gases concentrations will have a profound effect on global river discharges as compared to the effects of natural long-term Holocene climatic variability that is dominated by orbital forcing. For most of the rivers studied, the change in mean simulated discharge during the next 100 years compared to present will be similar to, or greater than, the discharge change simulated for the last 9000 years. This holds especially true for tropical rivers and for some temperate rivers in Europe and continental Asia. This study therefore supports the findings of research on the potential impacts of climate change on river hydrology, and the potential consequences on socio-economic activities that depend on the availability of water resources [*Arnell*, 2003; *Milly et al.*, 2005; *de Wit and Stankiewicz*, 2006; *Falloon and Betts*, 2006]. For future research, it would be useful to study the sensitivity of global river runoff under multiple scenarios and using multiple hydrological models in order to assess the influence of uncertainty related to both scenarios and models.

[14] **Acknowledgments.** We thank Jef Vandenberghe and Ronald van Balen for reviewing our paper. We thank Joe Alcamo for providing us with comments and reference outputs of the WaterGap model. Discharge data were provided by the National Center for Atmospheric Research (http://dss.ucar.edu/datasets), the RivDIS database (http://www.rivdis.sr.unh.edu/) and the SAGE database (http://www.sage.wisc.edu/riverdata/). Temperature and precipitation data were provided by the Climatic Research Unit [*Mitchell and Jones*, 2005]. This project was conducted under the programmes BSIK CS7 and BSIK ACER. Finally, we thank the two reviewers for their valuable comments.

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